Design Analysis for Solar Sailing from Geosynchronous Transfer Orbit

Kyle T. Ressler
Graduate Research Assistant
Dr. Michael Swartwout
Faculty Advisor
Washington University in St. Louis, MO 63130

As deep space exploration progresses the need for efficient means of spacecraft propulsion are essential. Current research is proving solar sailing to be both a cost effective and feasible form of maneuvering small spacecraft. Historically, to avoid the effects of atmospheric drag, solar sails have been designed to escape Earth orbit from altitudes greater than 10,000 kilometers. To increase the versatility of solar sails and to take advantage of the more frequent secondary payload options on geosynchronous transfer orbit launches, a GTO capable solar sail is proposed. A solar sail capable of GTO flight would provide small organizations and universities a feasible and cost-effective alternative to traditional propulsion for deep space missions.

This paper examines the problem of using traditional solar sail designs, square and heliogyro, in GTO's by establishing a set of design requirements. The designs are evaluated based upon these requirements, and finally based upon the traditional sail's poor performance a new hybrid solar sail is proposed that offers both high maneuverability and the ability to withstand the effects of low-altitude sailing.

Introduction

In light of recent material and electronic advances, solar sailing is regaining popularity as a potential source of spacecraft propulsion. Solar sailing is a means by which a spacecraft can use a sail to reflect photons from light. In the process of reflecting light, the spacecraft can pick up the momentum from each individual photon, thus creating a small but steady thrust. This phenomenon is shown in Figure 1. Due to the minimal but endless supply of thrust supplied by the Sun, solar sails are ideal for small mass high energy interplanetary missions [1, 2].

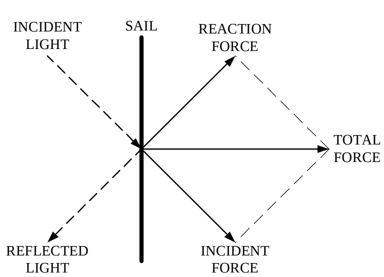

Figure 1 – Forces exerted on Solar Sail due to light [3]

Although the actual idea of the solar sail was conceived in the 1920's, by Konstantin Tsiolkovsky and Fridrickh Tsander, it was not until the proposed Halley Comet Rendezvous Mission (NASA) of the 1970's that the idea was given serious consideration [3]. The last few decades have brought unprecedented advances in both composite materials and microelectronics. These advances have finally provided the necessary building blocks to make solar sailing cost-effective and feasible. Evidence of this are the numerous solar sail missions currently being developed, such as: Cosmos 1 (The Planetary Society), ODISSEE (DLR), Encounter (Team Encounter), and the Solar Blade (Carnegie Mellon University). All of these missions are utilizing modern, low-mass, high strength materials and many of the microelectronic devices commonly used in today's small spacecraft community.

This resurgence of interest in solar sailing is coinciding with a time of increased space accessibility. Now more than ever, it is easier for small businesses and universities to build small spacecraft. This increased accessibility is due, in part, to the ever shrinking size of electronic components and the opportunity to place small spacecraft in secondary payload positions. Thus, as the ability to build smaller low-mass solar sails increases, the opportunity to place these spacecraft in low-cost secondary payloads also increases.

To date no mission has successfully demonstrated a working solar sail. If any mission is successful in demonstrating a solar sail, it could open the door to a whole new world of possibilities for the small spacecraft community. A successful mission would mean that there exists potential of a cost-effective and low stowage volume means of interplanetary propulsion. The question still remains; could solar sails really be applicable to the small spacecraft community? The answer lies in their ability to handle low-altitude sailing.

To date all planned solar sail missions have starting altitudes greater than 10,000 kilometers, with Encounter being the highest at 64,000 kilometers [4]. High-altitudes are desired for solar sail missions because they expedite Earth escape and allow atmospheric effects to be ignored. However, to reach high-altitudes requires large launch vehicles or secondary buses, both of which can dramatically increase mission cost and complexity making it impractical for small organizations [1]. Thus, in order for solar sailing to become widely accessible, a sail must be developed that can operate within low-altitudes and take advantage of the more frequent low-cost secondary payload GTO (Geosynchronous Transfer Orbit) launches.

This paper examines the problem of low-altitude capable solar sails by establishing a set of design requirements. This set is then used to analyze existing square and heliogyro solar sail designs to determine if they are capable of low-altitude flight. Using data from the sail analysis, a new hybrid sail capable of high-maneuverability and low-drag configurations is proposed as a potential design solution for cost-effective low-altitude sailing.

1 - Low-altitude Mission Types

One benefit of low-altitude solar sailing over high-altitude is its accessibility. Traditional solar sail designs require that they start and operate out of the Earth's atmosphere. This requirement limits them to a small number of deep space launches, as seen in Figure 2, or it requires that they carry a secondary bus. To a small organization or university, both of these alternatives are extremely costly in both development time and money. Solar sails that are able to overcome the hazards posed by low-altitude atmospheric conditions have the ability to utilize more launch opportunities, allowing them to get into orbit more frequently and at a lower cost. The ideal launch for low-altitude capable solar sails is the GTO launch, and as shown in Figure 3, GTO launch frequency has been increasing since 1989.

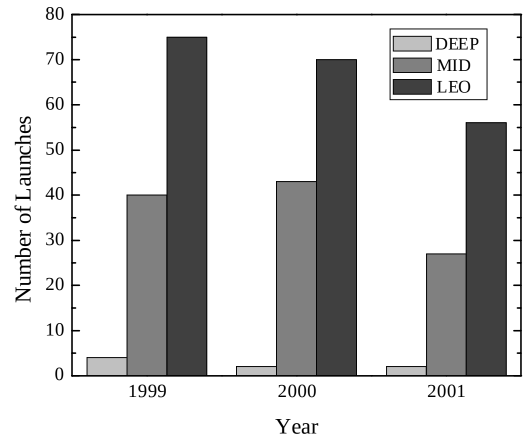

Figure 2 – Number of Launches Per Year (Compiled from [5])

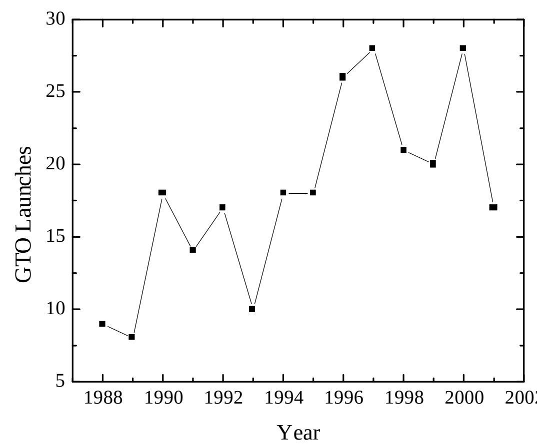

Figure 3 – Number of GTO Launches Per Year (Compiled from [5])

Another significant consideration in low-altitude sailing missions is time. Due to the minimal amount of thrust present, solar sails require a large amount of time to accelerate and thus take a long time to escape Earth orbit. This time can be further increased by starting in low-altitude orbits and by combating the effects of atmospheric drag. Therefore, missions that require short escape or interplanetary arrival times are not well suited for solar sails.

Low-altitude escape solar sail missions are well suited for small organizations and universities. Both are likely to have relatively small budgets and be willing to accept long mission times. The appeal of low-altitude solar sails is made clearer by examining traditional rocket propulsion as an alternative for putting probes into deep space. Using rocket propulsion is likely to provide much shorter mission times, but will be much more expensive and suffer limited launch availability due to increased size and mass. The increased cost of rocket propulsion will simply make it unfeasible to most small organizations. However, taking a dramatic reduction in cost and increase in launch accessibility for longer mission times is a tradeoff many organizations would be willing to make.

2 - Low-altitude Solar Sail Requirements

A solar sail capable of withstanding the atmospheric effects of low-altitude flight has dramatically different requirements than its high-altitude counterpart. For a high-altitude sail, the main concern is maximizing solar thrust as it orbits the Earth in an effort to escape Earth orbit. Low-altitude sailing is made significantly more complex by the presence of atmospheric drag. A low-altitude sail must not only maximize its solar thrust by positioning itself with respect to the sun, but it must also be capable of minimizing atmospheric drag.

Maintaining solar thrust in high-altitude orbits is a relatively straightforward principle; comprised mainly of keeping the reflective side of the sail pointed in a direction so as to maximize the orbital acceleration. By gradually increasing the orbital velocity the sail will spiral outward until it ultimately overcomes the effects of the Earth's gravity. Once the sail is outside of the effects of gravity, the control scheme can change depending upon the mission's ultimate destination.

Low-altitude thrust maintenance is complicated by the need to balance the negative effects of atmospheric drag with the need for forward acceleration. This type of thrust optimization requires complex sensing and actuation and an agile solar sail capable of switching from low-drag to maximum thrust configurations in a matter of seconds. Low-drag configuration is typically accomplished by turning the spacecraft edgewise, thus making the craft long and flat in the face of atmosphere. In low-altitudes, if a craft is unable to change configurations quickly it could suffer catastrophic mission failure in two ways; the sail could fail to overcome the negative effects of drag causing the craft to get stuck in a downward orbit, or it could fail to maneuver to low-drag configuration and the sails or booms could suffer damage due to atmospheric drag. In the latter case, excessive flapping of sails could cause tearing or the added aerodynamic load could be enough to bend the booms or other components into failure. It should be noted that the initial orbit seen by a low-altitude GTO solar sail will be the most dangerous. This will occur because the sail will be spiraling outward, and as the orbit increases the craft will be allowed more time to make its maneuvers and be experiencing less atmospheric drag as the perigee moves outward. There are five basic requirements that a low-altitude solar sail must meet, they are outlined in Table 1 and will be discussed in-depth in the following sections.

Table 1 – Low-Altitude Solar Sail Requirements

1	High Characteristic Acceleration
2	Low Mass
3	Low Stowed Volume
4	High Maneuverability
5	Structurally Robust

2.1 - High Characteristic Acceleration

With the fundamental differences between deep space and low-altitude sailing established, it is necessary to develop basic measurements to compare existing solar sail designs and determine their low-altitude feasibility. The most common metric used to compare solar sail designs is the characteristic acceleration (a_o). Characteristic acceleration is a measure of the maximum amount of acceleration a sail can have at a distance of 1 astronomical unit from the Sun. In order to calculate a_o we need to know the craft's mass (m) and sail area (A), the solar radiation pressure ($P_S = 4.56 \cdot 10^{-6} N \cdot m^{-2}$) the craft will experience, and the sail's reflective efficiency (η). Equation (2.1) shows the formulation of the characteristic acceleration equation.

$$a_o = \frac{2\eta P_S}{\left(m/A \right)} \tag{2.1}$$

a_o is a convenient means of measuring the amount of time it will take a solar sail to escape Earth orbit, and ultimately reach its destination. However, a high a_o becomes increasingly more important when dealing with low-altitude solar sails because it can dramatically affect mission times. Prior studies have concluded that a a_o less than $0.27\ mm \cdot s^{-2}$ will produce unreasonable escape times. Therefore, this will serve as our minimum allowable a_o.

2.2 – High Maneuverability

Although the characteristic acceleration is an important metric, for sails flying in low-altitudes there are other measurements equally as important for mission success. The sail's ability to maneuver in and out of low-drag configurations is a key component of this success. This maneuver is characterized by a rotation from the maximum acceleration (unit normal parallel to the velocity vector) to minimum drag (unit normal perpendicular to the velocity vector). The allowable maneuvering time varies slightly with different orbits and is defined in this study by the amount of time it will take the sail to travel from the semilatus rectum to the point where the orbit intersects the Earth's atmosphere. This definition was chosen because there exists a certain worst case scenario for solar sails in a GTO Earth escape trajectory. This scenario occurs when the craft is perpendicular to the sun at the semilatus rectum (Figure 4); this can be problematic, because if the sail were to maintain this angle it could confront the Earth's atmosphere at a dangerous angle, possibly resulting in catastrophic failure.

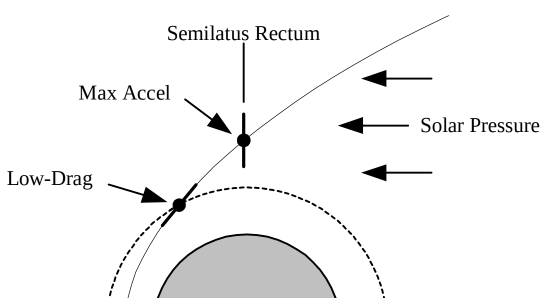

Figure 4 – Maneuvering Time Diagram

For this study we will assume the solar sail is starting in a GTO orbit with an apogee altitude of 35,768 kilometers and a perigee altitude of 500 kilometers. To calculate the maximum allowable maneuvering time we must first define the semi-major axis (a) and eccentricity (e) of the orbit. Using the radius of the Earth ($r_E = 6,378\ km$), we obtain $a \approx 24,500\ km$ and $e \approx 0.72$. With the Earth's Gravitational Constant ($\mu = 3.986 \cdot 10^5\ km^3 \cdot s^{-2}$) and Equation (2.2) we can calculate the total orbital period to be $P = 38{,}164.6\ seconds$.

$$P = 2\pi\sqrt{\frac{a^3}{\mu}} \tag{2.2}$$

Since we are interested in the orbital time from the semilatus rectum (point 3) to the intersection with atmosphere (point 4) we must calculate the true anomaly from perigee (f) for two movements, shown in Figure 5 as f_1 and f_2. To aid in calculating f, we will utilize the equivalent orbital time from point 6 to point 7. It should be noted that the orbit is symmetric, and thus the orbital times from point 3 to 4 and point 6 to 7 will be identical. By calculating f_1 and f_2 we are then able to compute the orbital time of each path, and then by subtracting these times we obtain the maximum maneuvering time (t_m).

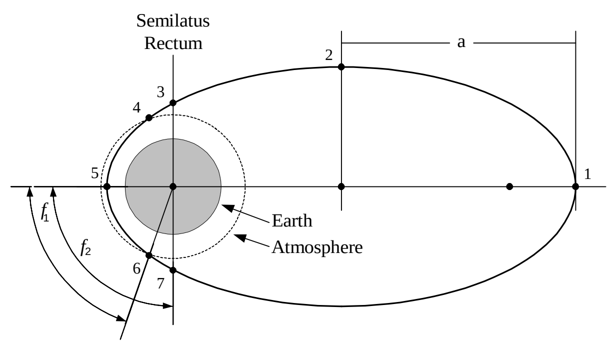

Figure 5 – GTO Diagram

Equation (2.3) will allow us to calculate the true anomaly from perigee to the point where the orbit intersects the Earth's atmosphere.

$$f_1 = a\cos\left(\frac{1}{e}\left(\frac{a(1-e^2)}{(r_E + r_{atm})} - 1\right)\right) \tag{2.3}$$

Using $r_{atm} = 1500\ km$ we obtain a $f_1 = 0.80$. f_2 is equal to $\pi/2$, as shown in Figure 5. Now using Equation (2.4), we can calculate the eccentric anomaly (u) for each orbit, and with Equation (2.5) we can calculate the maneuvering times to be $t_1 = 604.5\ seconds$ and $t_2 = 1,624.7\ seconds$.

$$u = \cos^{-1}\left(\frac{e + \cos(f)}{1 + e\cos(f))}\right) \tag{2.4}$$

$$t = (u - e\sin(u))\frac{P}{2\pi} \tag{2.5}$$

Thus, a maximum maneuvering time of 17 minutes, about 2.6% of the total orbit period, is required for the solar sail's first orbit. It should be noted that the initial orbit will require the fastest maneuvering time, and as the orbit increases the amount of maneuvering time will also increase.

High maneuverability can also be advantageous once the solar sail has escaped Earth orbit. Many of the proposed solar sail missions could benefit greatly from agile spacecraft (i.e. asteroid chaser). For instance, a slow maneuvering solar sail would be capable of performing an asteroid flyby or rendezvous mission, but an agile solar sail could be capable of hunting down an asteroid and orbiting or tracking it for extended periods of time. The difference in the two scenarios could be immeasurable for researchers and explorers collecting data from the asteroid.

2.3 – Low Mass and Volume

Two important requirements are low overall mass and volume. For this discussion, low mass will be considered to be less than 50 kilograms, and be broken into two categories; spacecraft mass and payload mass. Spacecraft mass includes all parts of the solar sail needed to fly (sail, booms, avionics, etc.) and the payload mass is anything additional that is not required for flight (experiments, communication hardware, etc.). Low-volume is considered to be stowed volume, because a small payload is more likely to gain access to a launch. However, it should be noted that as the solar sail itself grows its stowed volume often grows with it.

Since the overall mass is capped at 50 kilograms, a low-altitude design with a low spacecraft mass would be preferred over a design just capable of low-altitude flight. The importance of low overall mass can easily be seen by examining Equation (2.1). Notice that as the mass increases the characteristic acceleration will decrease unless the sail area is also increased. As noted above, if the characteristic acceleration is reduced it could mean longer mission times or mission failure.

The need for low mass and volume is also a major factor when looking for potential launches. Ideally, for cost and accessibility reasons, it would be advantageous to be a secondary payload. However, many launch vehicles have strict mass and volume requirements for secondary payloads. For instance, the NASDA H-IIA requires secondary payloads to be less than 50 kg and the Ariane V requires secondaries less than 80 kg.

2.4 – Structurally Robust

The effects of atmospheric drag on the structure of the solar sail need to be considered. While operating in or near low-altitudes it is expected that the solar sail structure will encounter forces that could affect the structural integrity of the spacecraft. The sail itself is likely to undergo flapping and increased pressure due to air flow, and this increased pressure could cause significant loads to be applied to the structure of the spacecraft. As a basic comparison of loads we will compute the force induced by solar pressure and the drag force caused by low-altitude sailing. A $2,000\ m^2$ sail in full solar pressure will see a force of $9.12 \cdot 10^{-3}\ Newtons$. The drag force ($F_D$) seen by a solar sail facing atmosphere full on can be computed using Equation (2.6).

$$F_D = \frac{1}{2} C_D \rho A v^2 \qquad (2.6)$$

Using a coefficient of drag equal to $C_D = 1.0$, density of air at $500\ km$ of $\rho = 7.22 \cdot 10^{-12}\ kg \cdot m^{-3}$ [6], sail area of $A = 2,000\ m^2$, and a maximum orbital velocity of $v = 9,980\ m \cdot s^{-1}$ we are able to compute a drag force equal to $0.72\ Newtons$. The F_D is about eighty times greater than the force caused by solar pressure. Due to the large F_D induced by sailing normal to the atmosphere it is necessary that the solar sail be capable of minimizing this force. For comparison, a solar sail traversing through atmosphere in a low-drag configuration with a frontal area of $A = 1.3\ m^2$ and using a $C_D = 0.5$ has a drag force equal to $2.34 \cdot 10^{-4}\ Newtons$. Thus, the low-drag configuration has a drag force three orders of magnitude smaller than the sail normal to atmosphere. However, since numerous solar sail designs and configurations exist it is difficult to formulate a specific set of requirements for all solar sail types. Therefore, structural robustness will be examined case by case.

2.5 – Requirements Summary

It is the aim of this analysis to determine how feasible it is to fly existing solar sail designs (square sail and heliogyro) in low-altitudes. Based upon the earlier discussion, and in order to maintain consistency in the comparison of different designs, a certain set of standard design requirements and specifications, outlined in Table 2, will be used.

Table 2 – Standard Design Requirements and Specifications

Min. Characteristic Acceleration	0.27 mms^{-2}
Max. Spacecraft Mass	50 kg
Max. Low-drag Maneuver Time	17 min
Sail Area	2000 m^2
CFRP Boom Linear Density	100 g/m
CFRP Boom EI	5000 Nm^2
Payload Mass	10 kg

A standard sail made of aluminum and chromium coated Kapton (Figure 6) with a η of 0.85 and an area of $2,000\ m^2$ will be used for this analysis. Therefore, the sail alone will constitute about 3.5 kg of spacecraft mass.

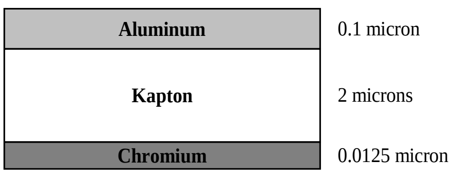

Figure 6 – Standard Sail Material Diagram [3]

Standard booms will also be used, where applicable, to maintain consistency among the designs. Existing designs, such as Encounter, have linear boom densities as low as $14.1\ g/m$, with an $EI \approx 2,200\ N \cdot m^2$ [4]. However, Team Encounter has the distinct advantage of starting outside of the Earth's atmosphere. Structures being subjected to the effects of atmospheric drag will need to be much more robust, and as such we will assume a linear density of $100\ g/m$, with an $EI \approx 5,000\ N \cdot m^2$ adequate. CFRP (Carbon Fiber Reinforced Plastic) booms exhibiting such characteristics are currently feasible, and are being developed and demonstrated by ESA/ESTEC and INVENT [2].

3 – Design Analysis

All of the proposed solar sail missions to date are based upon two main sail designs; the square sail and the heliogyro (Figure 7). Therefore, generic versions of these two configurations were analyzed using the specified low-altitude design requirements. Due to their poor performance in meeting these requirements, they were deemed unfit for low-altitude sailing. Thus, a third configuration was developed and analyzed that is more apt for low-altitude sailing.

3.1 – The Square Sail

The square sail is by far the most widely examined solar sail configuration, due to its simple design and structure. Organizations such as Encounter and DLR are planning missions utilizing square sails. The design is essentially a large square sail supported by booms, with the payload located at the center. The major variations explored on this design are with respect to the sail, booms, and control mechanism.

To alleviate the need to create one giant sail and to ease in deployment, the sail is usually split into four or more triangular sections. The boom structures are typically in the shape of a "+", but it is also possible to put booms around the perimeter of the craft.

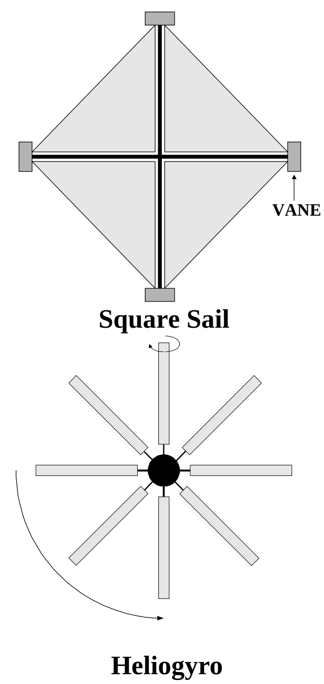

Figure 7 – Two Main Solar Sail Configurations

The most significant difference in designs is with the control mechanism. Control can be obtained by using vanes located at the corners of the sail, reaction wheels, thrusters, center of mass positioning, or in combination.

This investigation will focus on the square sail pictured in Figure 7, with cross shaped booms, centrally located payload, and vane controlled attitude. The overall design of this configuration is simple and robust. It does not require any outside efforts (i.e. spinning) to maintain its shape once deployed and it is geometrically simple. Stowage of square sails has also proven to be surprisingly efficient. Advanced folding methods of sails and rolling of booms have helped keep reasonable stowage volumes feasible. However, these advantages come at the cost of mass.

A square sail of this design exhibiting $2,000\ m^2$ of sail area must have four 32 meter centrally mounted booms. The overall structural mass is dependant upon the linear density of the booms selected. Using the previously defined CFRP booms, the total boom mass is about 13 kg. An additional 2 kg of rigging will be allocated to allow for sail seaming and attachment and also 10 kg for avionics, basic structure, and four $5\ m^2$ attitude vane assemblies. Adding in the predefined standard sail, the craft mass is about 28.5 kg, without the payload. A total mass breakdown for the square solar sail is shown in Table 3. With the above specifications the square sail has a a_o of $0.544\ mm \cdot s^{-2}$. It should be noted that the addition of payload mass will dramatically affect the a_o, allocating only 10 kg of payload mass will bring the characteristic acceleration to $0.403\ mm \cdot s^{-2}$.

Table 3 – Mass Breakdown of Square Solar Sail

Part or Assembly	Mass
Four 32 meter CFRP Booms	13 kg
Sail Rigging	2 kg
Avionics	2 kg
Basic Structure	4 kg
Four 5 m^2 Attitude Vane Assemblies	4 kg
Standard 2000 m^2 Sail	3.5 kg
Standard Payload	10 kg
TOTAL SQUARE SAIL MASS	**38.5 kg**

While it seems more than feasible to design a square sail to meet the mass, volume, and a_o requirements of low-altitude sailing, the craft has yet to prove its agility. The moment of inertia of a square sail (neglecting sail material and payload) rotating about its vertical axis is shown in Equation (3.1), where λ is the boom mass per unit length [3].

$$I_S = \frac{\lambda}{3\sqrt{2}} A^{\frac{3}{2}} \tag{3.1}$$

Using $\tau = Fl$ we can calculate the torque caused by a $5\ m^2$ attitude vane in full solar pressure to be $7.36 \cdot 10^{-4}\ N \cdot m$ and utilizing $\tau = I\alpha$ we are able to determine the angular acceleration of the craft to be $3.4 \cdot 10^{-7}\ rad \cdot s^{-2}$. In order to simplify the calculation of the amount of time required to complete a 90º turn we will assume a constant α for the first 45º and $-\alpha$ for the deceleration from 45º to 90º. The simplification allows us to utilize Equation (3.2).

$$\theta = \theta_o + \frac{1}{2}\alpha t^2 \tag{3.2}$$

Using Equation (3.2) we are able to compute a rotational time of about 71 minutes, well above the desired time of 17 minutes. This time could be decreased by reducing λ or by increasing the vane area, but design changes in these areas could decrease boom robustness and increase craft mass. In fact, in order to meet the required 17 minute maneuvering time the square sail would require a vane with an area of $86.4\ m^2$. This is far too large of a vane to be considered when compared to the overall spacecraft size.

3.2 – The Heliogyro

The heliogyro sail has been the subject of in depth analysis since its introduction in 1967, by Richard MacNeal. The heliogyro gained increased attention when it was considered by NASA for a Halley Rendezvous mission, but the concept was eventually discarded in favor of an ion-thruster craft. More recently Carnegie Mellon University investigated the possibility of flying a nanosatellite version of a heliogyro [7].

The conceptual basis of the heliogyro is based on a helicopter's rotors. As shown in Figure 7, the heliogyro is made up of a centrally located payload and control structure with long thin blades extending outward. The blades constitute the sail of the craft, and can by cyclically rotated to obtain attitude control. The overwhelming advantage of the heliogyro is its low stowage volume and ease of deployment. This is due in part to the lack of boom structure required by the blades. The blades are typically comprised of long 1 to 3 meter wide sheets that can be stowed in rolls, obviating the need for complex folding and packaging. Deployment of the blades is obtained by rotating the base craft and gradually unrolling the stowed blades. This rotation causes a centrifugal force which acts to rigidize the otherwise thin film blades and must be maintained throughout the mission. Centrifugal force is selected as the preferred method for rigidizing the long, narrow sails on the basis of minimum weight and minimum complexity [8].

To obtain the $2{,}000\ m^2$ sail area required by this study, there are numerous blade configurations possible. The length, width, and number of blades could be varied to generate any number of craft designs. Since one of the goals of this study is to maintain low cost and complexity we will utilize 1 meter wide sheets, of the previously defined sail material, because they are readily available and would not require any additional tooling costs. A four-blade sail will also be used, because as the number of blades increase so do the complexities of the base craft and the control scheme. With the configuration of the sail determined, we are able to define the dimensions of each blade at 1 meter wide, 500 meters long, and a predefined thickness of about 2.1 microns.

As previously defined the sail will constitute about 3.5 kg of spacecraft mass. The craft will also require support structures at the base of the blades and drive motors to control the cyclic blade rotations used in attitude control. We will allocate 18 kg for the avionics, basic craft structure, and the four blade support structures and motors. The total mass breakdown for the heliogyro is outlined in Table 4. These allocations bring the total heliogyro mass to 21.5 kg, resulting in a a_o of $0.721\ mm \cdot s^{-2}$ without payload. Adding in an additional 10 kg of payload will result in a a_o of $0.492\ mm \cdot s^{-2}$.

Table 4 – Mass Breakdown of Heliogyro

Part or Assembly	Mass
Four Blade Support Structures	4 kg
Four Drive Motors	6 kg
Avionics	4 kg
Basic Structure	4 kg
Standard 2000 m^2 Sail	3.5 kg
Standard Payload	10 kg
TOTAL HELIOGYRO MASS	**31.5 kg**

Without considering the effects of low-altitude flight, the heliogyro appears to be promising candidate, offering ease of stowage and deployment and a near 20% increase in a_o over the square sail. However, no heliogyros have been developed to operate within the effects of atmosphere. The added drag forces of low-altitude flight could easily cause the blades to bend or tear, and if a blade were to become detached there is a high probability of impact with the remaining blades, likely leading to catastrophic failure [3]. To overcome these drag forces it would be necessary to develop some sort of stiffening agent in the blades (i.e. advanced sail material, structural booms, or higher rotational rates). The development of a material, with the blades dimensions, that could withstand even minor atmospheric flight and not add unreasonable cost or mass is currently unfeasible. The addition of booms to the blades is also a consideration, but adding structure to the 500 meter blades would eliminate the initial stowage and deployment advantages of the design and add significant mass. Increasing the rotational rate of the craft would also cause increased stiffening in the blades, but this can cause other issues with the design. As the spin rate is increased the blades themselves will also undergo increased tension, requiring additional structure or advanced materials to prevent failure. The increased spin will also increase the complexity of the control scheme, because the blades must be operated cyclically to perform maneuvers.

Regardless of the apparent problems with the blade dynamics in low-altitude flight, investigation into potential low-drag configurations of the heliogyro offers interesting discussion. The heliogyro has two distinct possible low-drag configurations; the first is similar to that of the square sail, where the craft would perform a 90º turn and face the atmosphere edgewise. The second and preferred option, utilizes the blades abilities to turn about their axis. In the first scenario, the maneuver would require a cyclic rotation of blades in which a single blade position (not blade) would maintain greater solar pressure than the other three causing a gradual pitch to progress. The second scenario, utilizing the blades drive motors, could simply rotate the blades so that the sails would face their edges into the oncoming atmosphere. In this case the necessary rotational time could simply be factored into the motor design. However, both of these possibilities have the same inherent problem, the craft is still spinning. As the heliogyro rotates as it passes through the atmosphere the blades will be confronting air, inducing bending and drag forces on the thin blades. This effect could easily cause the flimsy film blades to become streamers behind the craft or tear away causing mission failure.

3.3 – Summary of Design Analysis

The square and heliogyro solar sails have proven to be excellent design considerations for high-altitude flight, but they have also shown to have major drawbacks while operating in low-altitudes. The square sail offers a simple and robust structure at a reasonable mass, but has serious maneuverability problems. The heliogyro offers a relatively low overall mass, but the required spinning for blade rigidity makes it unsuitable for atmospheric conditions. A summary of each sails performance in the design analysis is provided in Table 6.

A possible solution for a low-altitude solar sail configuration would be to combine the positive aspects of each design while eliminating those that prevent them from being feasible in low-altitudes. A potential design would seek to keep the simple and robust structural geometry of the square sail, while offering high agility. Although the heliogyro has proven itself to be unfit for low-altitude flight, the crafts ability to rotate its blades offers insight into increasing a craft's agility. With only these two design considerations it is possible to envision a third type of solar sail, one which has the look of a square sail, but the ability to rotate its sails via drive motors located at the base of the craft. This configuration, named the Diamond Hybrid, will be analyzed as a third candidate for low-altitude sailing.

4 – The Diamond Hybrid

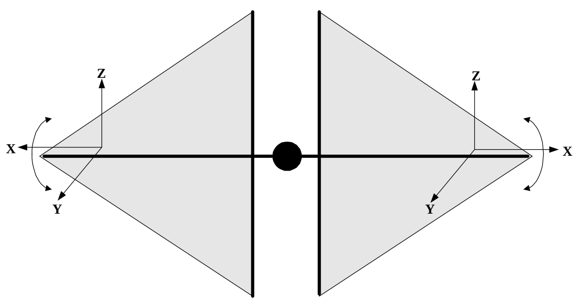

Figure 8 – Diamond Hybrid

The diamond hybrid sail combines numerous attractive qualities of the square and heliogyro solar sails. The basic design is made up of four independent triangular sails mounted in pairs to a central craft, forming a shape similar to the square sail. Each pair of sails is supported by two booms in a "T" structure, which are then mounted to a drive motor, like the blades of a heliogyro, allowing each sail to rotate independently (Figure 8). Attitude is controlled by various sail rotations, either independently or in combination. Stowage volumes are similar to that of the square sail, being slightly larger due to the addition of two additional vertical booms.

The basic geometry of the diamond hybrid is similar to that of the square sail's, but its structural makeup is different. The lateral booms are basically the same, with the exception of their ability to rotate about their axis. The most obvious difference is with respect to the vertical booms. The square sail has single vertical booms each attached to two sails, while the diamond hybrid has four booms coupled in pairs. Each pair is independent of the other and attached to its own sail.

Although the sails of the diamond hybrid will be rotated the lateral booms, being along the rotational axis, will be largely unaffected by these maneuvers. Thus, their loading will be similar to that of the square sail. As such, we will assume that the CFRP booms specified for the square sail are adequate for the lateral booms. The vertical booms present a different situation. Being positioned perpendicular to the rotational axis they are likely to undergo substantial loading if the sails are rotated quickly. The vertical booms do have one advantage over those of the square sail; being laterally independent they are only required to handle the solar load of one sail. This situation presents an interesting tradeoff; if the craft can be designed so that rotation of the blades will not induce significant loading to the vertical booms, then a lighter and less stiff boom could be adequate, since they will only be required to support the load of one sail. However, if the booms are to be subjected to large rotational loads it is possible that a heavier and stiffer boom than the lateral boom will be required.

Before specifying a linear density and EI for the vertical booms, we will investigate the crafts agility. This will allow us to determine the rotational loads that will be seen by the vertical booms and use that information in determining their structural makeup. The diamond hybrid offers two potential low-drag configurations, shown in Figure 9; First, the craft could turn one of its sails edgewise to the Sun while leaving the other perpendicular. This would allow the craft to gradually turn about its axis, much like the square sail, and eventually face the atmosphere edgewise. With this maneuver the craft would be approaching the atmosphere with less frontal area and be in the shape of a "+." The second configuration would constitute rotating both blades about their axis so that the craft would face one side edgewise to the atmosphere, essentially slicing through the air.

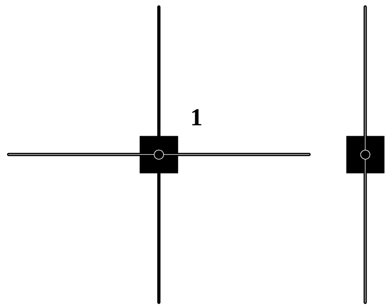

Figure 9 – Low-Drag Configurations 1 and 2

The second configuration is the preferred of two. This configuration provides the minimum frontal area and also takes advantage of the craft's ability to quickly rotate its sails, obviating the need to rely on solar pressure to convert to low-drag configuration. To determine the rotational acceleration (α) needed to rotate the sails 90º in under 17 minutes, we need to define the maneuver. The sails will be rotated 45º at a constant α for a period of 510 seconds (half of the maximum time), and then the remaining 45º at $-\alpha$. This will allow the sails to perform the rotation with minimal overshoot. α can be determined through Equation (4.1).

$$\theta = \theta_o + \omega_o t + \frac{1}{2}\alpha t^2 \qquad (4.1)$$

By setting $\theta_o = \omega_o = 0,\ \theta = \pi/4$, and $t = 510\ seconds$, we are able to solve for $\alpha = 0.6 \cdot 10^{-6}\ rad \cdot s^{-2}$. Utilizing this α with the defined maneuver we are able to obtain low-drag configuration in about 17 minutes. However, we need to determine if this rotation will cause unreasonable loading effects on the vertical booms. Using the mass moment of inertia of a rod, Equation (4.2), an assumed linear density of 100 g/m, and $\tau = I\alpha$ we are able to determine the torque created at the base of the 32 meter boom to be $1.64 \cdot 10^{-3}\ N \cdot m$.

$$I_{SR} = \frac{1}{12} ml^2 \qquad (4.2)$$

Using this torque we can calculate an equivalent distributed load (W) equal to that seen by the rotating rod of $W = 3.0 \cdot 10^{-6}\ N \cdot m^{-1}$. From Equation (4.3) we can then calculate the maximum deflection ($y_{\max}$) seen by this boom to be $y_{\max} = 8.4 \cdot 10^{-5}\ m$, using an $EI \approx 5{,}000\ N \cdot m^2$. Note that this maximum deflection will occur at the tip of the boom.

$$y_{\max} = \frac{Wl^4}{8EI} \qquad (4.3)$$

Noting that the deflection seen by the 32 meter boom is incredibly small, the maneuver is more than feasible and presents no substantial danger to the vertical booms. Based upon the crafts ability to convert to low-drag configuration and the minimal deflection seen by the vertical booms, CFRP standard booms have proven to be more than adequate. In fact, using these booms we are able to increase α to $0.01\ rad \cdot s^{-2}$ and still only see 0.139 meters maximum deflection. This increase in α allows the craft to switch to low-drag configuration in less than 30 seconds, offering an enormous increase in agility.

Using the above specifications the diamond hybrid's booms comprise a total of 19.2 kg of spacecraft mass. It should be noted that although the diamond hybrid's booms have the same specifications as those used on the square sail, the total mass will be greater due to the two additional vertical booms. Allocating the same 2 kg of rigging, seen on the square sail, and an additional 15 kg of mass for basic structure, avionics, boom attachment, and drive motors the overall spacecraft mass becomes 39.7 kg, shown in Table 5. This corresponds to a a_o of $0.391\ mm \cdot s^{-2}$. With the standard payload addition of 10 kg, the a_o is $0.312\ mm \cdot s^{-2}$.

Table 5 – Mass Breakdown of Diamond Hybrid

Part or Assembly	Mass
Six 32 meter CFRP Booms	19.2 kg
Sail Rigging	2 kg
Avionics	2 kg
Basic Structure	6 kg
Two Drive Motors	7 kg
Standard 2000 m^2 Sail	3.5 kg
Standard Payload	10 kg
TOTAL DIAMOND MASS	**49.7 kg**

Although the diamond hybrid is substantially more massive than the square and heliogyro solar sails, it has proven itself to be much more agile and apt for low-altitude flight. The increase in mass has a significant effect on the crafts ability to have a high a_o, ultimately leading to longer escape times. The final diamond hybrid analysis results are summarized in Table 6.

Table 6 - Summary of Design Analysis

	Square	Heliogyro	Diamond	Requirement
Sail Mass (kg)	3.5	3.5	3.5	3.5
Boom Mass (kg)	13	0	19.2	-
Rigging (kg)	2	0	2	-
Basic Structure (kg)	4	4	6	-
Avionics (kg)	2	4	2	-
Attitude Control Mass (kg)	4	10	7	-
Payload (kg)	10	10	10	10
TOTAL MASS (kg)	38.5	31.5	49.7	< 50
Characteristic Acceleration (mm/s^2)	0.403	0.492	0.312	> 0.27
Low-Drag Maneuvering Time (min)	71	n/a	0.5	17
Low Stowage Volume	Good	Excellent	Good	-

5 – Conclusion and Future Work

This design study has shown that there exists the potential of using geosynchronous transfer orbit launches to place solar sails into deep space without the need for secondary buses. This potential is significant because it means that there exists a low-cost option for deep space exploration, and thus increases mission scope for many small organizations and universities.

Through analyzing the traditional solar sail designs in a GTO orbit scenario we were able to quantify the aspects of the designs that prevented them from being feasible in the low-altitude portion of the orbit. This allowed the development of a hybrid solar sail that combined the positive attributes of both the square and heliogyro, while minimizing the effects of their negative attributes. The result is a craft not only capable of handling the effects of atmospheric conditions, but offering tremendous increases in agility. These increases in agility could ultimately lead to more effective solar sail missions outside of Earth orbit.

The diamond hybrid does have some concerns, its major drawbacks are its high mass and thus low a_o. The total spacecraft mass comes within 300 grams of being over the 50 kg design requirement, making it by far the most massive of the three designs investigated. However, this mass could be decreased in a couple of ways. Further investigation into the boom structure could yield designs that offer similar stiffness at lower masses, or show that less massive booms are adequate for GTO missions. Also, as small satellite components continue to evolve into smaller and less massive parts, it may be possible to accomplish mission goals with smaller payloads. The relatively low a_o of the diamond hybrid will lead to longer escape times, which ultimately means longer mission times. To obtain a higher a_o it is also possible to increase the sail area. Depending upon the linear density of the booms chosen for a given design it may be advantageous to increase the sail area, but this would need to be investigated on a case by case basis. However, to small organizations wishing to place a spacecraft capable of deep space exploration into orbit the added mission time is likely an acceptable alternative, in view of the other more costly options.

Future Work:

With the diamond hybrid's apparent feasibility established, more detailed analysis of the dynamic effects of low-altitude sailing will be necessary. This study examined only the basic requirements for low-altitude sailing. Before the sail could truly be deemed capable of escaping Earth orbit from a GTO trajectory detailed investigation into the craft's control schemes and dynamic atmospheric loading will need to be examined.

Acknowledgements:

This work was carried out at Washington University in St. Louis. The author would like to thank his past advisors, Dr. Mark Nagurka and Dr. Joseph Majdalani, and his current graduate advisor, Dr. Michael Swartwout, for their unwavering support and patience. Special thanks to Kyle Brucker, Julie Maule, and Jeremy Neubauer for their efforts and support.

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